

Structure, Dynamics, and Physical Properties of the Warm LISM Within the Local Bubble

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Objectives and Methodology of the LISM Program

- Develop a three-dimensional model for the warm gas clouds inside the Local Bubble (within $\log N_{\text{HI}} = 19.2$, about 100 pc). Relate to other phenomena in the LB (like magnetic field and serendipity).
- Based on kinematics (common velocity vectors) and whether or not there are common physical properties (T , ξ , $D(\text{Fe})$, and $D(\text{Mg})$).
- Using high-resolution UV spectra from HST/GHRS, HST/STIS, ground-based Ca II, and future HST/STIS.
- As a first approximation, assume that “clouds” are rigid ($\Delta V < 1.0$ km/s) homogeneous structures. Then will relax this assumption.
- Will compare with ionization models (e.g., Slavin & Frisch 2002) and models of transition layer heating by the hot gas (?) in the Local Bubble.
- Redfield & Linsky (ApJ 673, 283 (2008)).
- Linsky, Rickett, & Redfield (ApJ 675, 413 (2008)).

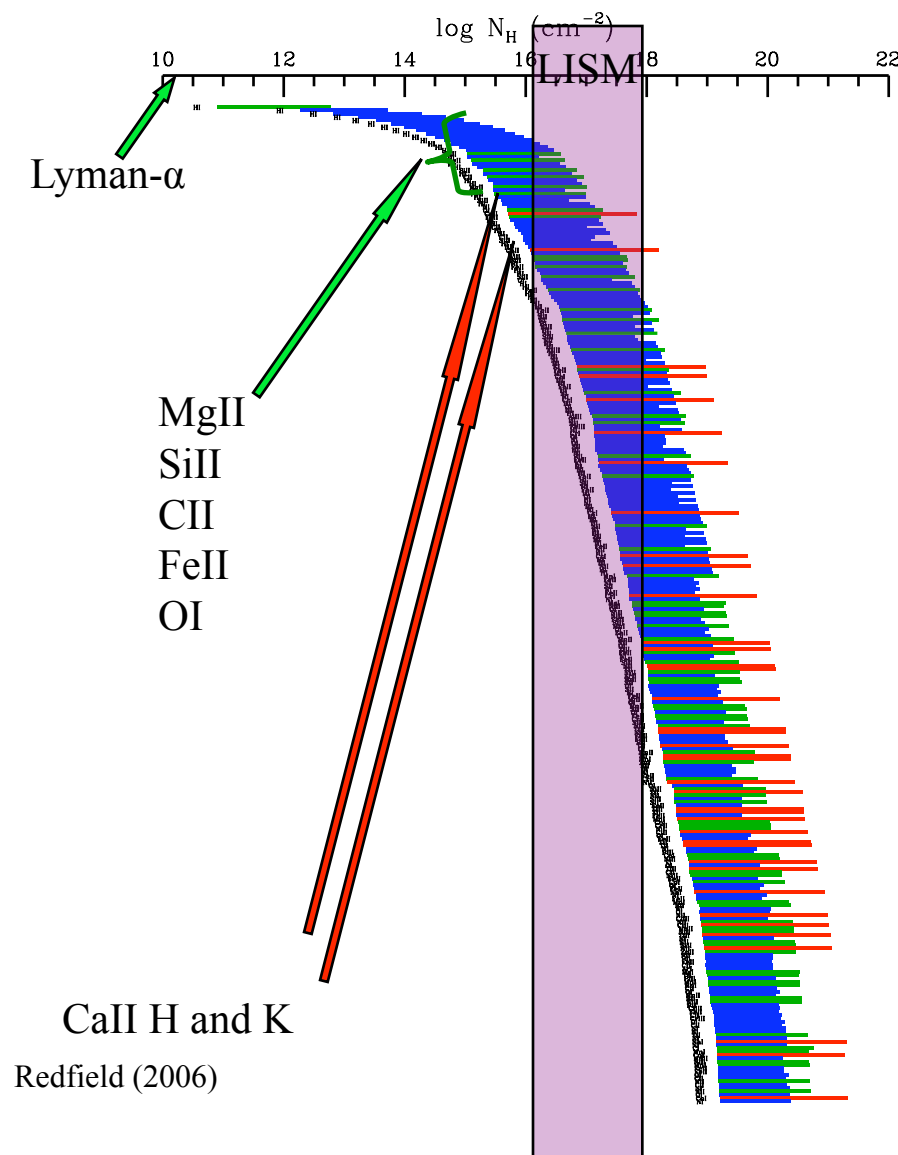
How do we measure properties of the LISM?

in situ

He I atoms *Ulysses* (Witte et al. 1996)
ISM dust w/ *Stardust* (Brownlee et al. 2003)
Voyager 1 in pristine ISM in only 45 years!

Absorption Line Spectroscopy

Most transitions lie in **FUV**
(900-1200Å), **UV** (1200-3000Å), and
optical (3000-10000Å)

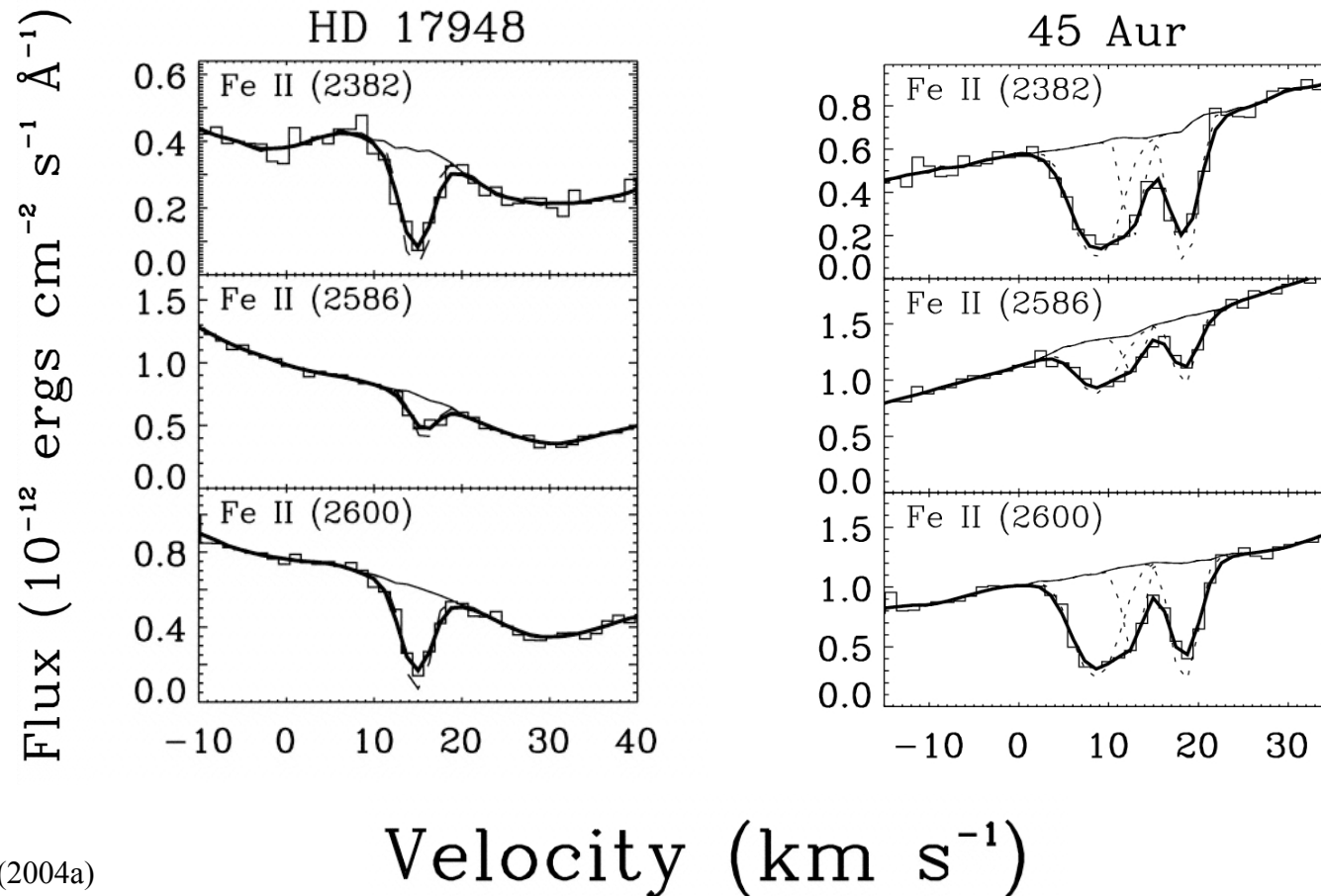


Observational Diagnostics

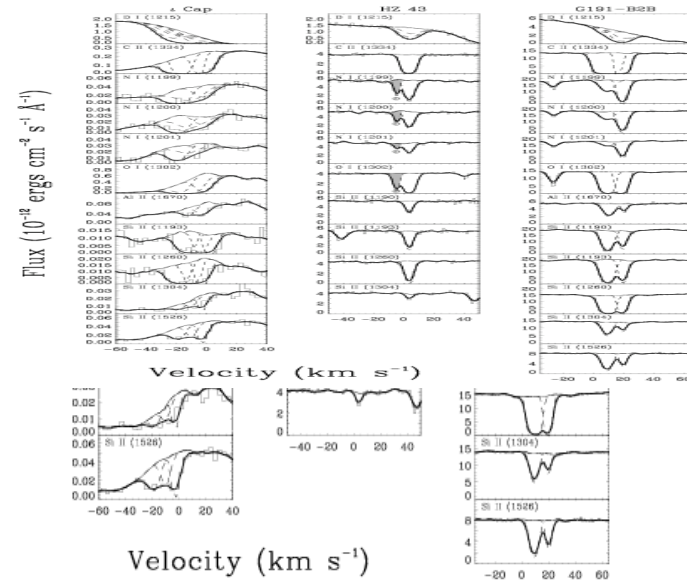
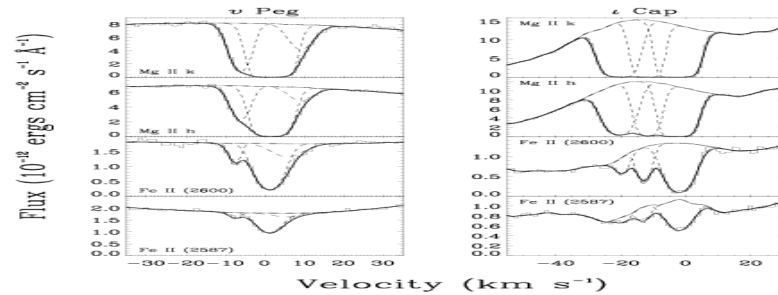
1 ion, 1 sightline



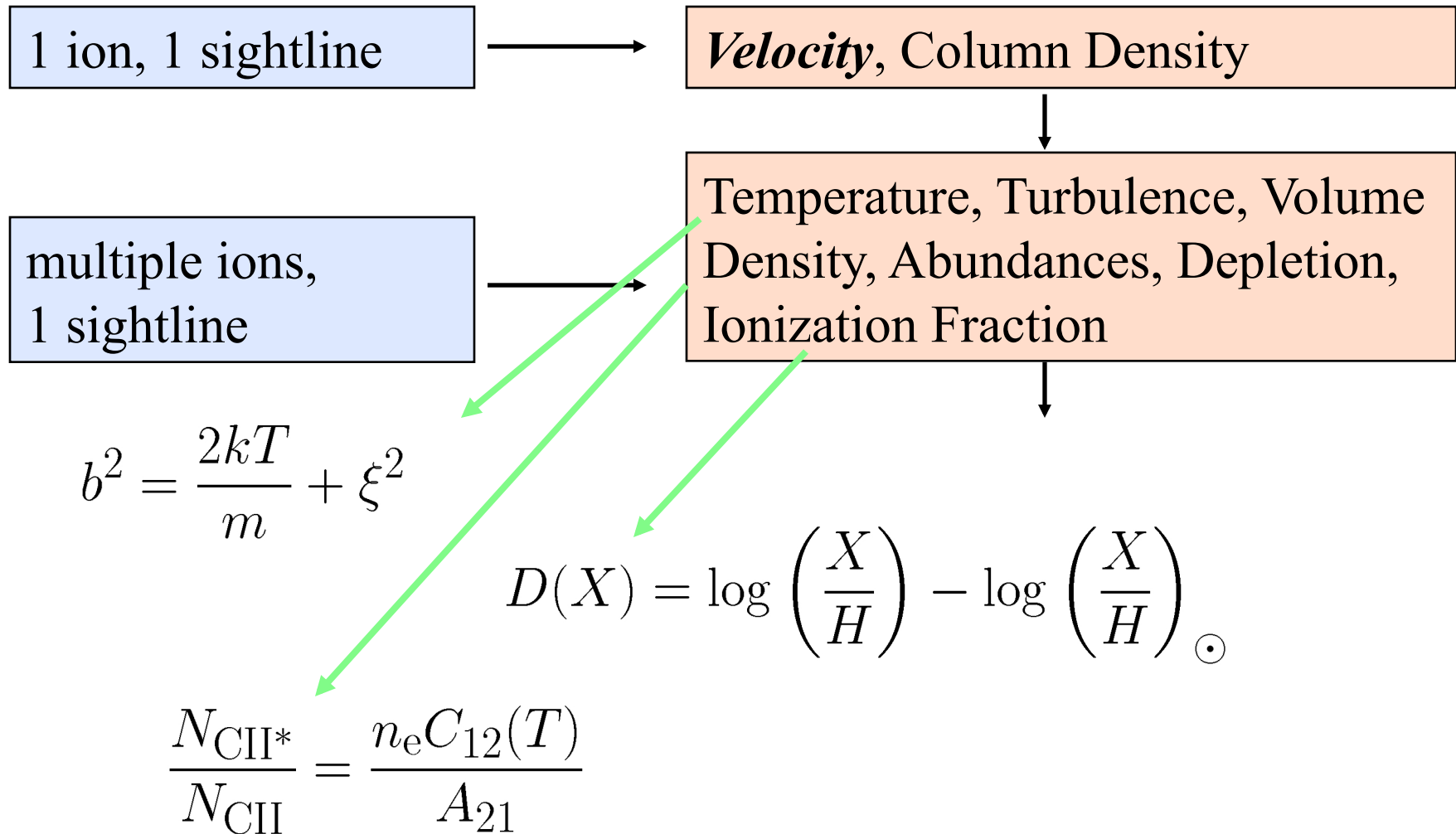
Velocity, Column Density

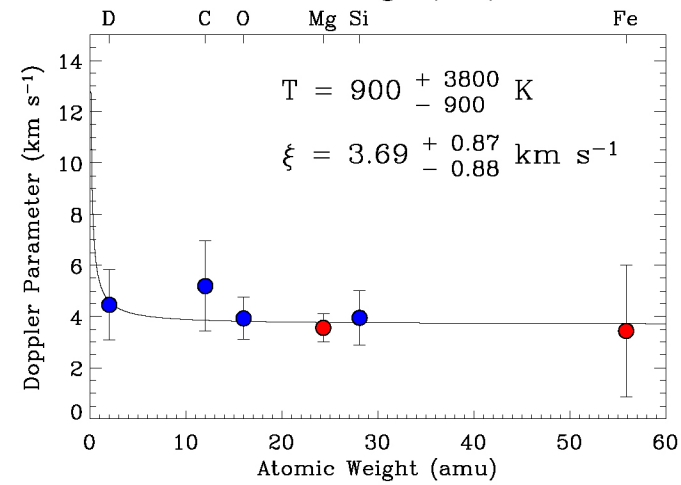
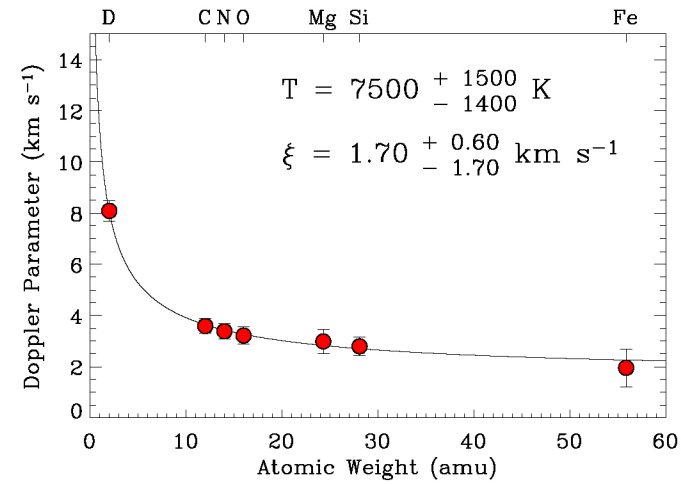
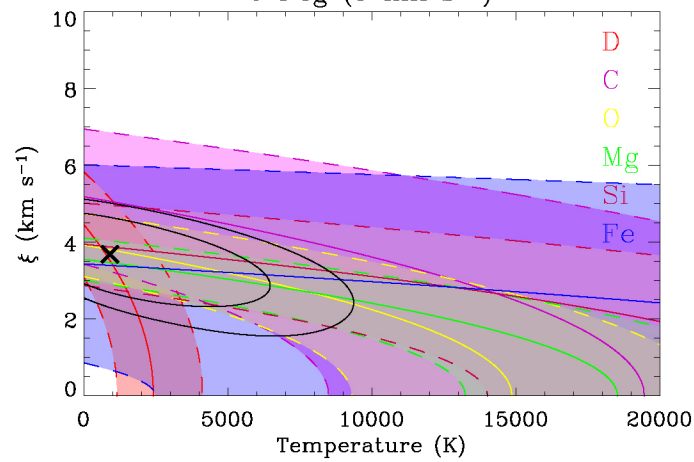
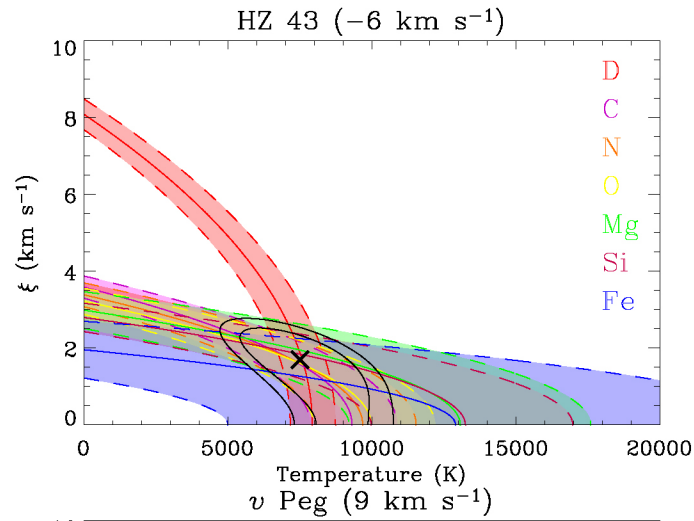


Examples of HST/STIS spectra of nearby stars showing two or more interstellar absorption lines



Observational Diagnostics

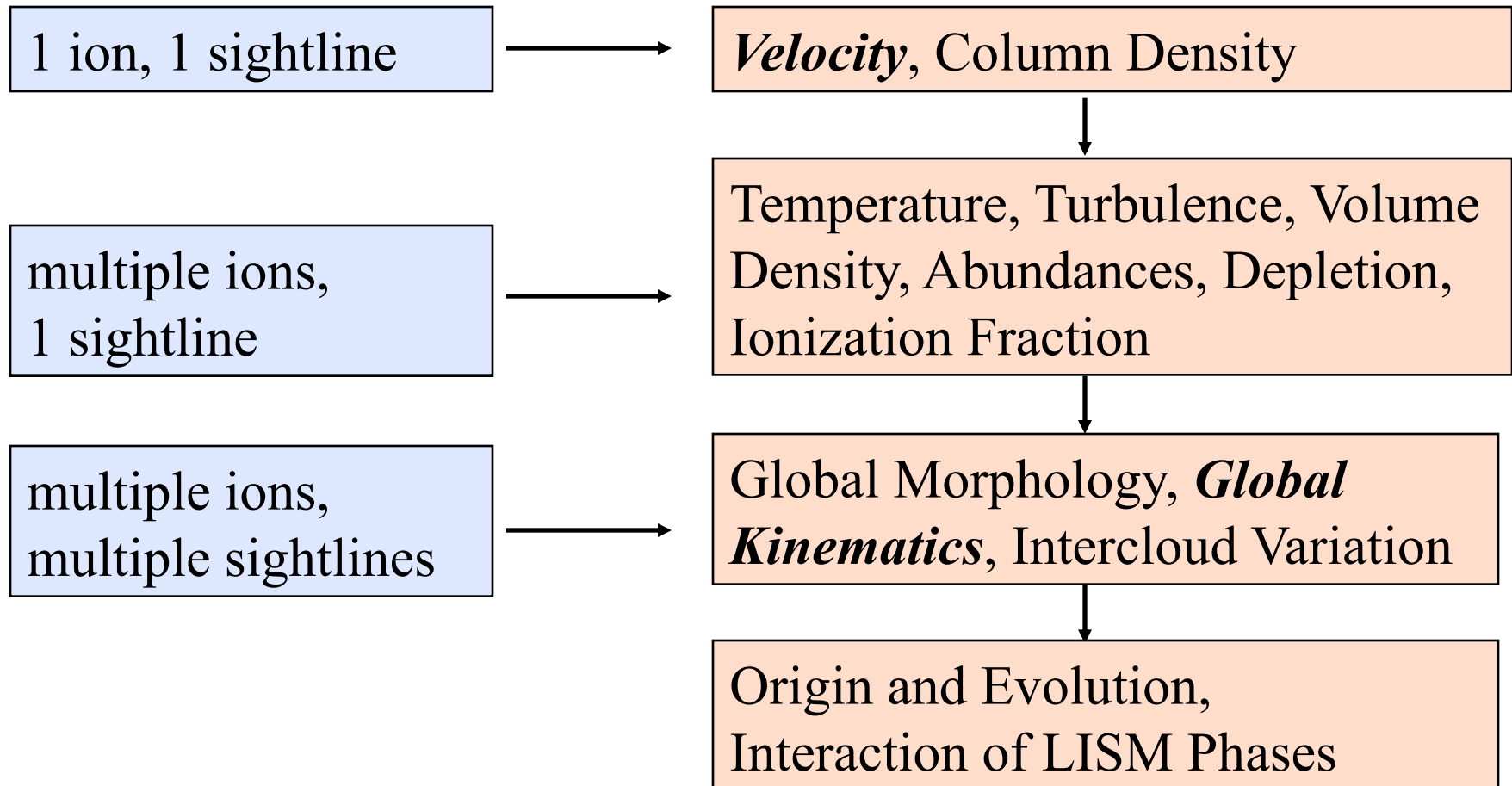




$$b^2 = \frac{2kT}{m} + \xi^2$$

Redfield & Linsky (2004b)

Observational Diagnostics



Global Kinematics

Our “observables”:

Centroid velocity (v_R) of LISM absorption, i.e., the radial component of the projected velocity in direction (l, b)

Assume the simplest dynamical structure: a single vector bulk flow.

$$v_R = v_0 (\cos b \cos b_0 \cos (l_0 - l) + \sin b_0 \sin b)$$

Questions:

Can the observed LISM velocities be characterized by a rigid bulk flow, or are they chaotic?

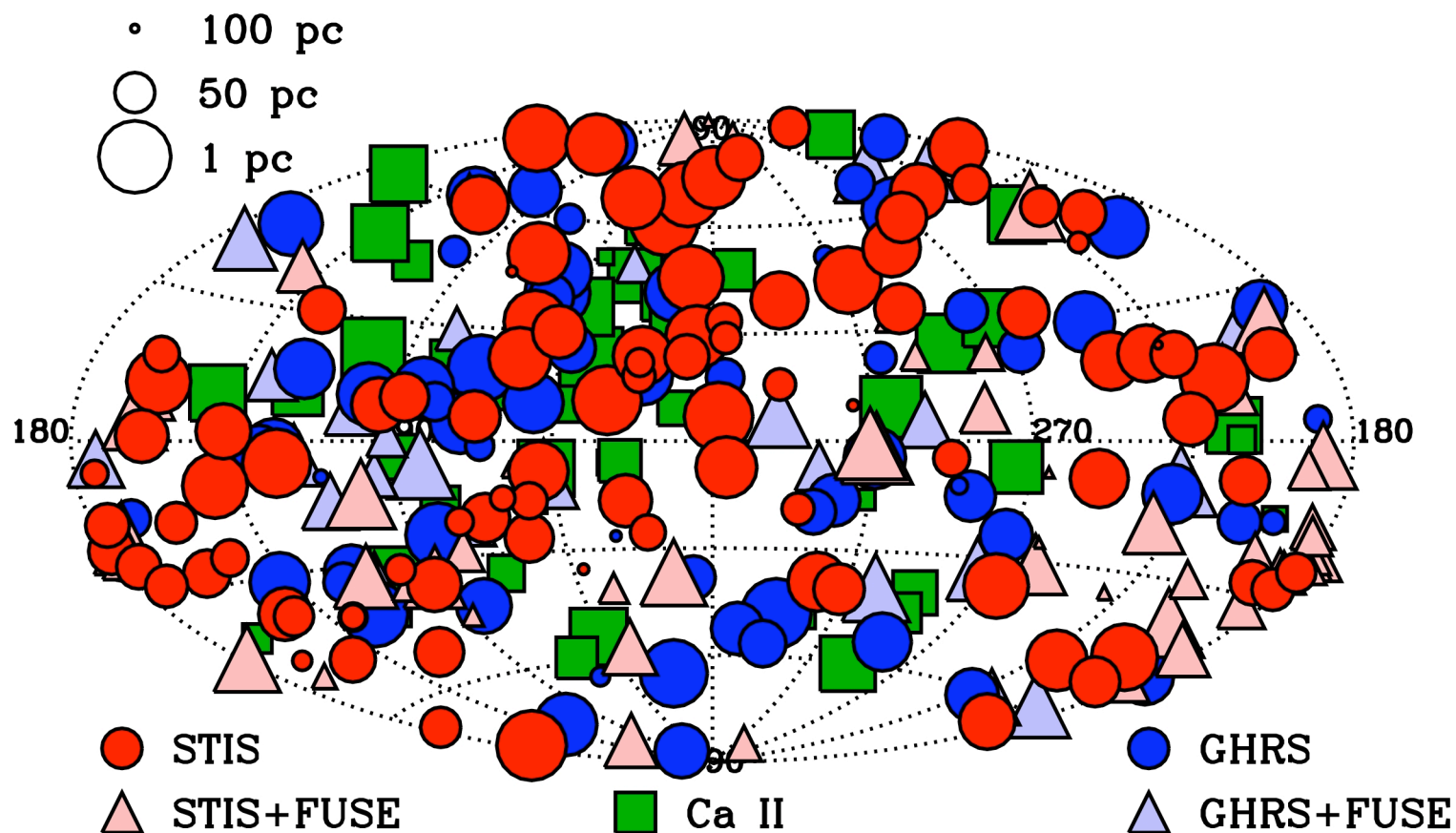
How significant are any departures from a rigid flow vector?

Is there a correlation between direction and departure from the bulk flow?

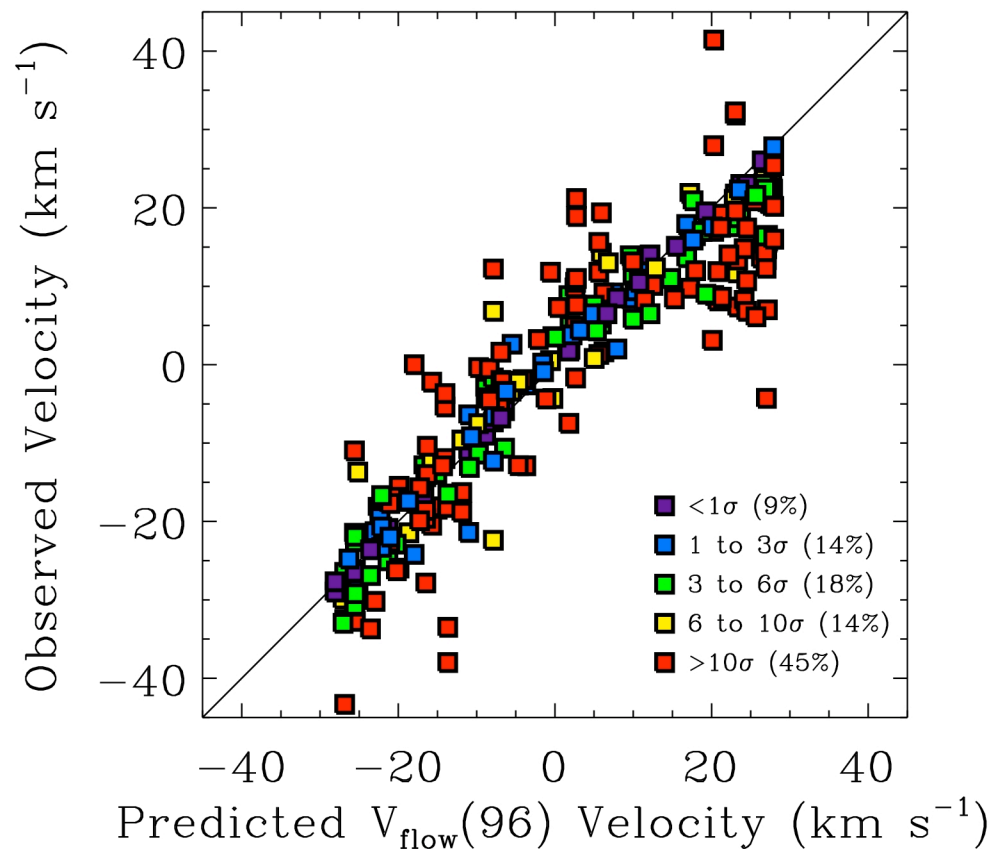
Can multiple velocity vectors successfully characterize the majority of LISM observations?

LISM Sample

160 targets within 100 pc observed at high and moderate resolution that contain 270 LISM absorption components (~60% of UV observations taken for other purposes).



LISM Sample



Dynamical Modeling Procedure

Iterative process:

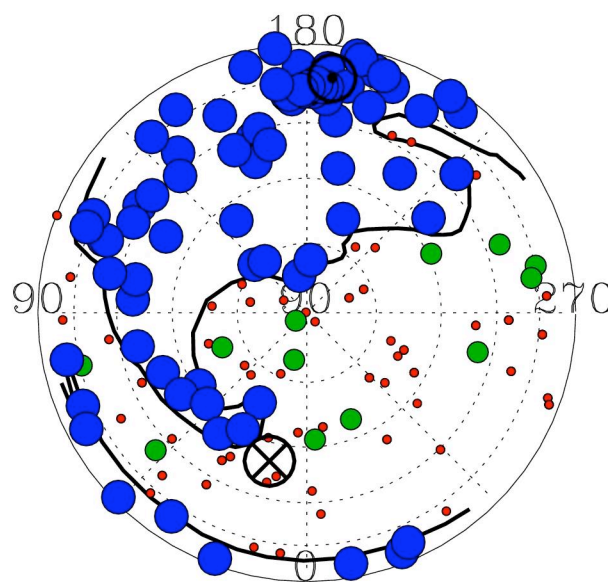
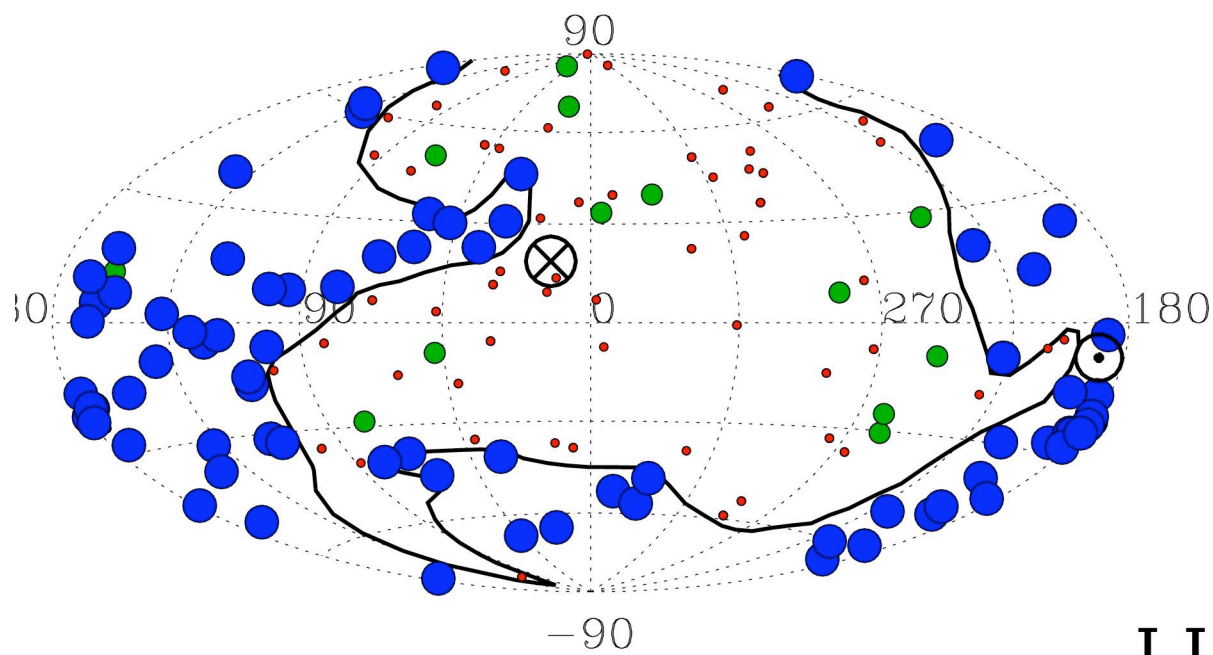
- Fit dataset
- Remove outliers (in velocity and space)
- Repeat until satisfactory fit (use F-test to determine stopping point)
- Remove successful dynamical cloud sightlines from dataset
- Start over.

Assumptions:

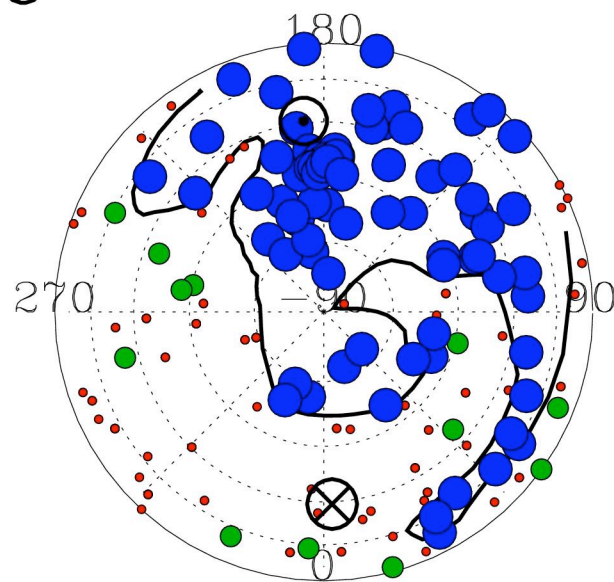
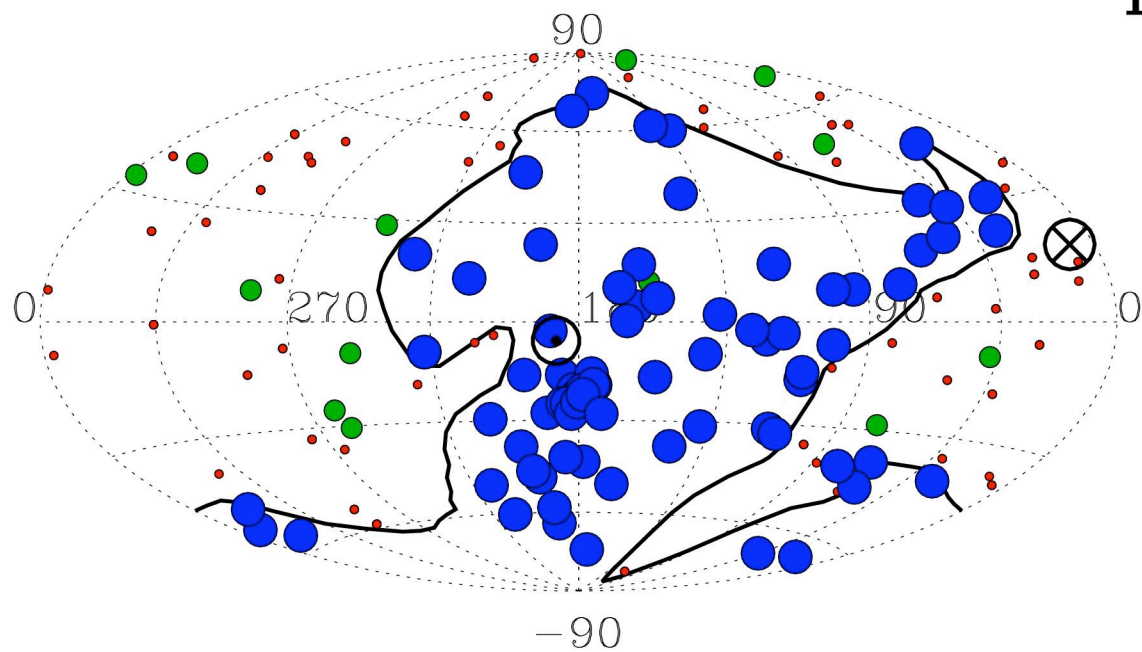
- All motions are rigid velocity vectors (i.e., a tensor dynamical characterization may result in two separate dynamical clouds, close in space, and with similar velocity vectors).
- The projected morphology of all clouds are contiguous (i.e., no “swiss cheese” clouds)

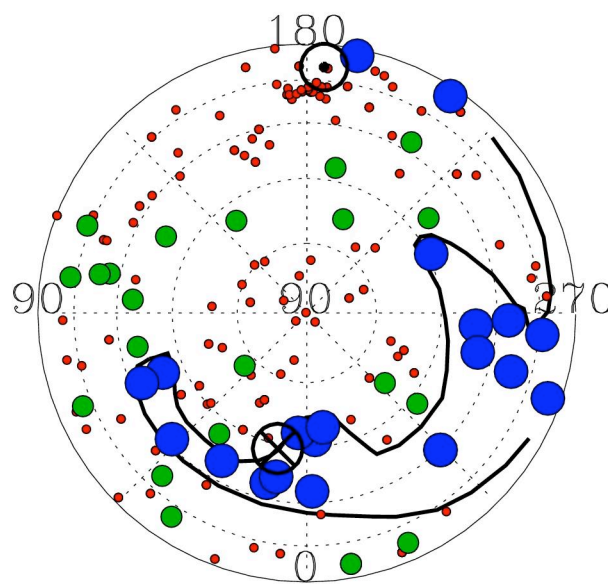
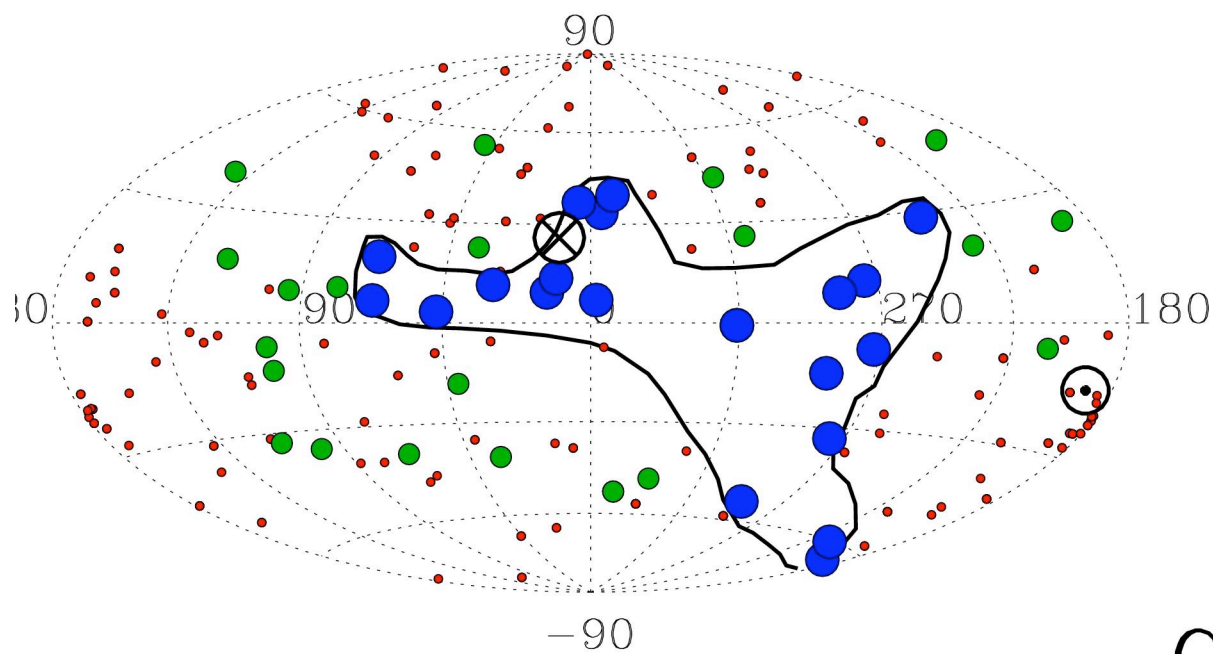
Results:

- Fits largest surface area structures first (e.g., LIC and G vectors derived immediately).
- 15 velocity vectors satisfy 80% of LISM database.
- All velocity vectors are similar, and approximately opposite to the motion of the Sun.
- About 1/3rd of the dynamical clouds are filamentary.
- Search for unique cloud properties.

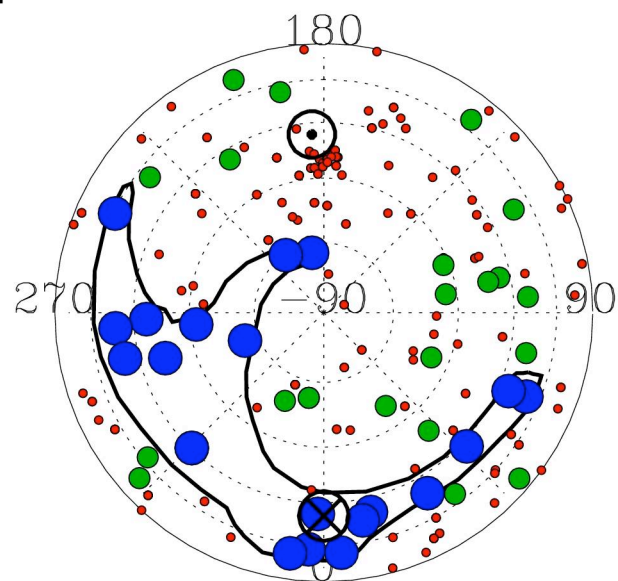
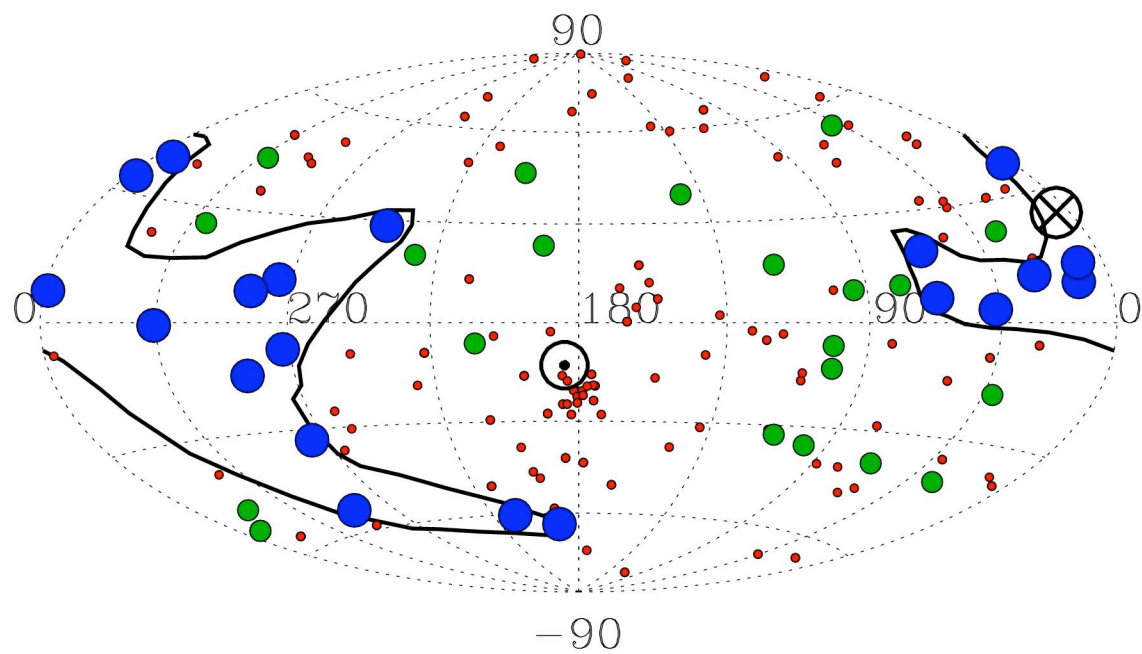


LIC





G



Do individual dynamical clouds have unique physical properties?

Table 17. Summary of Cloud Properties

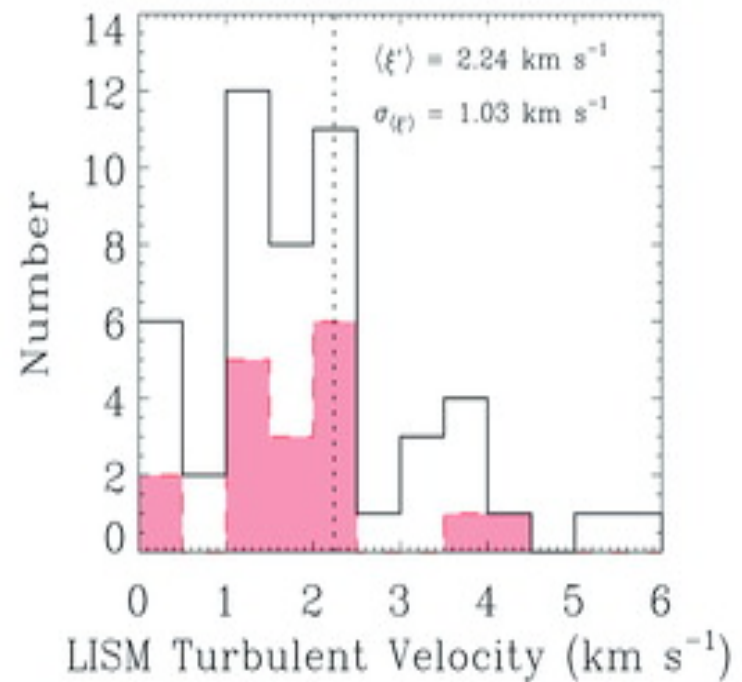
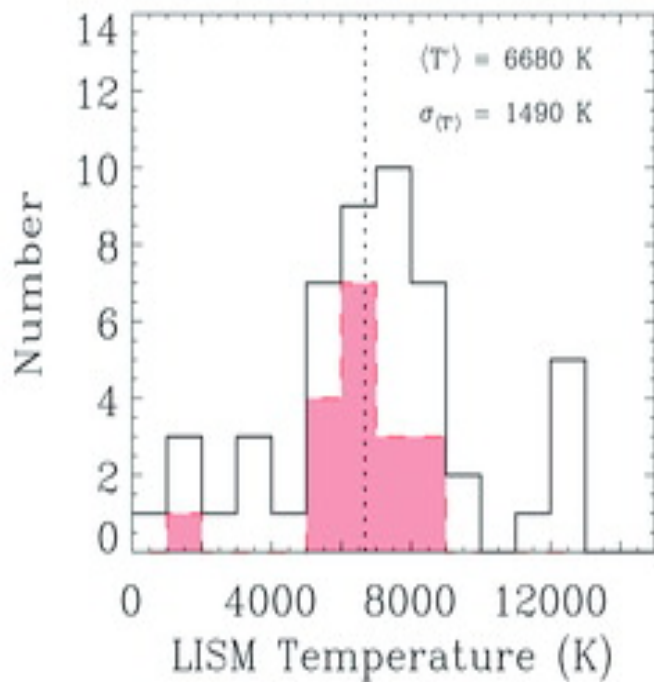
Cloud Name	# of Stars	Central Coord. $l(^{\circ})$ $b(^{\circ})$		Closest Star (pc)	Farthest Distance Constraint ^a (pc)	Surface Area	$\langle T \rangle$ (K)	# of Stars	$\langle \xi \rangle$ (km s ⁻¹)	# of Stars	$\langle D(\text{Fe}) \rangle$	# of Stars	$\langle D(\text{Mg}) \rangle$	# of Stars
LIC	78	170	-10	(0) ^b	...	(18270) ^c	7500 ± 1300	19	1.62 ± 0.75	19	-1.12 ± 0.10	12	-0.97 ± 0.23	21
G	21	315	+00	1.3	...	8230	5500 ± 400	5	2.2 ± 1.1	5	-0.54 ± 0.11	4	-0.36 ± 0.35	5
Blue	10	250	-30	2.6	...	2310	3900 ± 2300	3	2.64 ± 0.16	3	-0.84 ± 0.27	2	-0.51 ± 0.49	2
Mic	15	40	+15	5.1	3.5	3550	9900 ± 2000	4	3.1 ± 1.0	4	-0.92 ± 0.43	2	-0.03 ± 0.40	4
Hyades	14	180	-20	5.0	3.2	1810	6200 ± 3800	5	2.7 ± 1.2	5	-0.32 ± 0.62	4	-1.06 ± 0.47	5
Gem	10	300	+40	6.7	3.5	3300	6000 ± 1100	3	1.63 ± 0.41	3	-1.29	1	-1.05 ± 0.16	3
Leo	7	270	+55	11.1	8.5	2400	...	0	...	0	...	0	...	0
Eri	8	70	-20	3.5	...	1970	5300 ± 4000	3	3.6 ± 1.0	3	-0.39 ± 0.19	2	-0.15 ± 0.30	3
Dor	4	270	-50	11.7	10.4	1550	7000	1	5.5	1	-0.80	1	-0.65	1
NGP	15	5	+75	8.5	6.7	4020	8000 ± 600	4	1.23 ± 0.43	4	-1.04 ± 0.23	4	-0.89 ± 0.15	3
Aql	9	40	-05	3.5	...	2960	7000 ± 2800	3	2.07 ± 0.64	3	-0.96	1	-0.69 ± 0.21	3
Oph	6	45	+25	5.1	...	1360	1700	1	3.3	1	...	0	-0.84	1
Cet	5	290	-40	15.5	14.9	2270	6300	1	1.3	1	...	0	0.21	1
Vel	6	300	-45	14.9	11.7	2190	10600	1	3.5	1	...	0	-0.03	1
Aur	9	210	+10	3.5	...	1640	6710	1	1.2	1	...	0	-0.79	1

^aThe farthest star that is within 10° of the cloud that is closer than the closest cloud member.

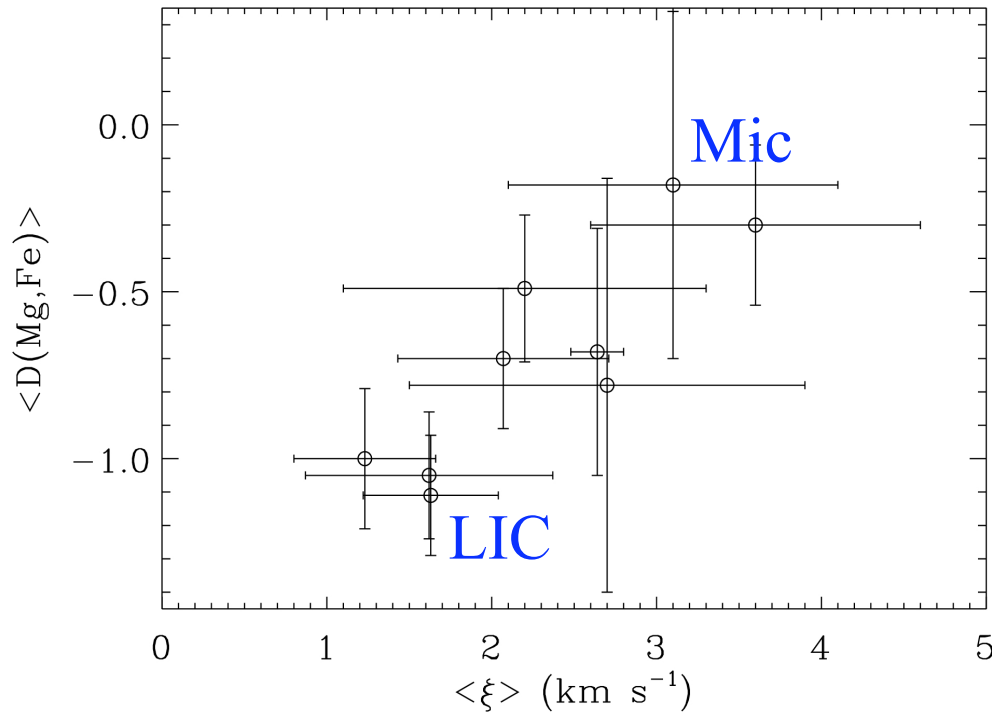
^b*In situ* measurements of the temperature and direction of the interstellar flow into the solar system indicates that the solar system is passing through LIC material (Möbius et al. 2004; Redfield & Linsky 2000).

^cBecause the LIC completely surrounds the solar system, its surface area is 4 π steradians or ~ 41250 square degrees. However, since we are near the edge of the LIC, there are areas of the sky for which we do not detect any LIC absorption. The angular area given here indicates the area of the detection boundary of the LIC.

Distributions of temperatures and
nonthermal broadening for warm clouds in
the Local Bubble with HST spectra (Redfield
and Linsky ApJ 613, 1004 (2004))



Turbulent Velocity and Depletion onto Grains



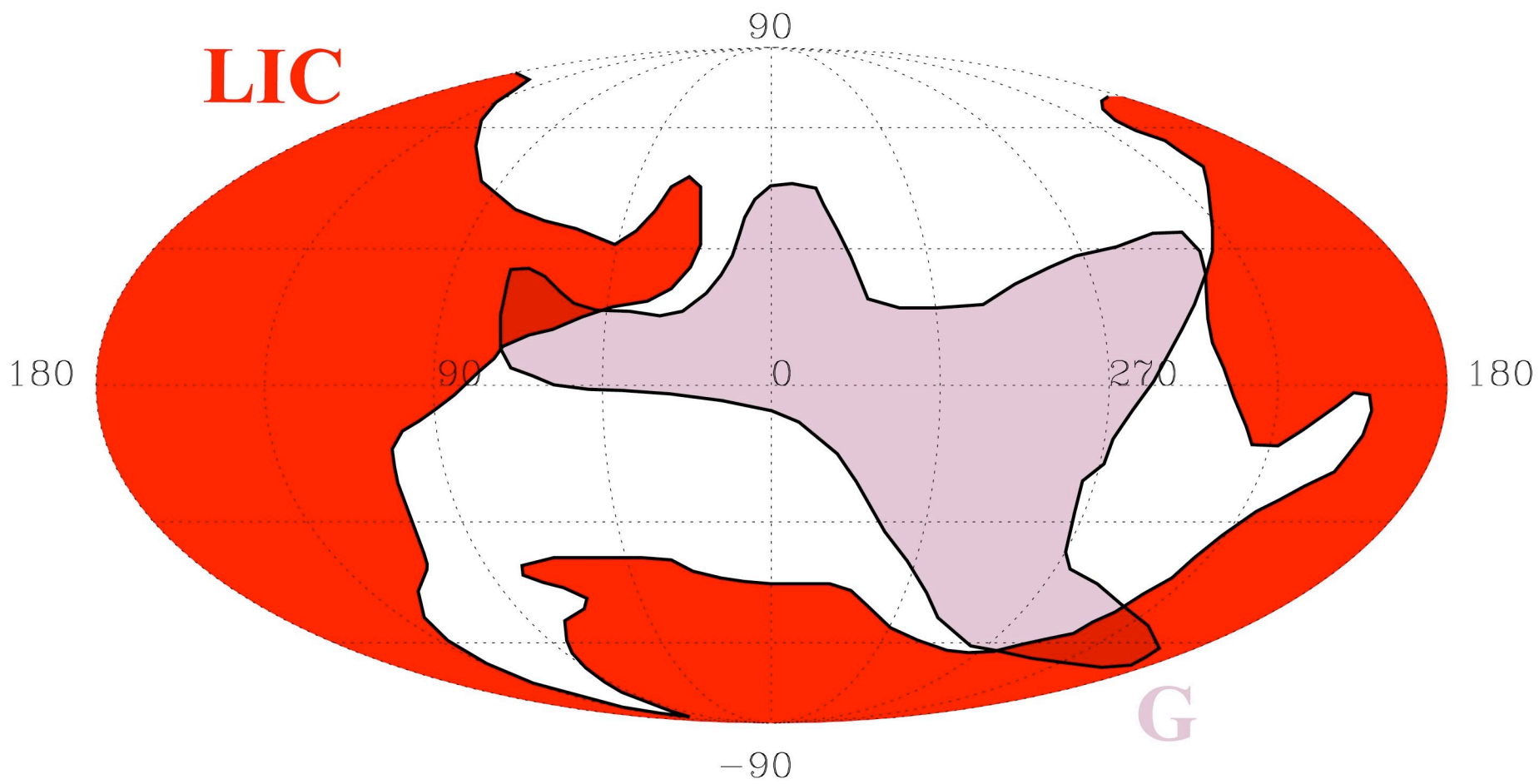
A clear correlation exists between turbulent velocity and depletion: $r \sim 0.85$ and $P_c \sim 0.21\%$.

Turbulent shocks could destroy grains and return ions to gas phase, thus decreasing magnitude of depletion.

Weak shock grain destruction also invoked to explain depleted deuterium (Linsky et al. 2006).

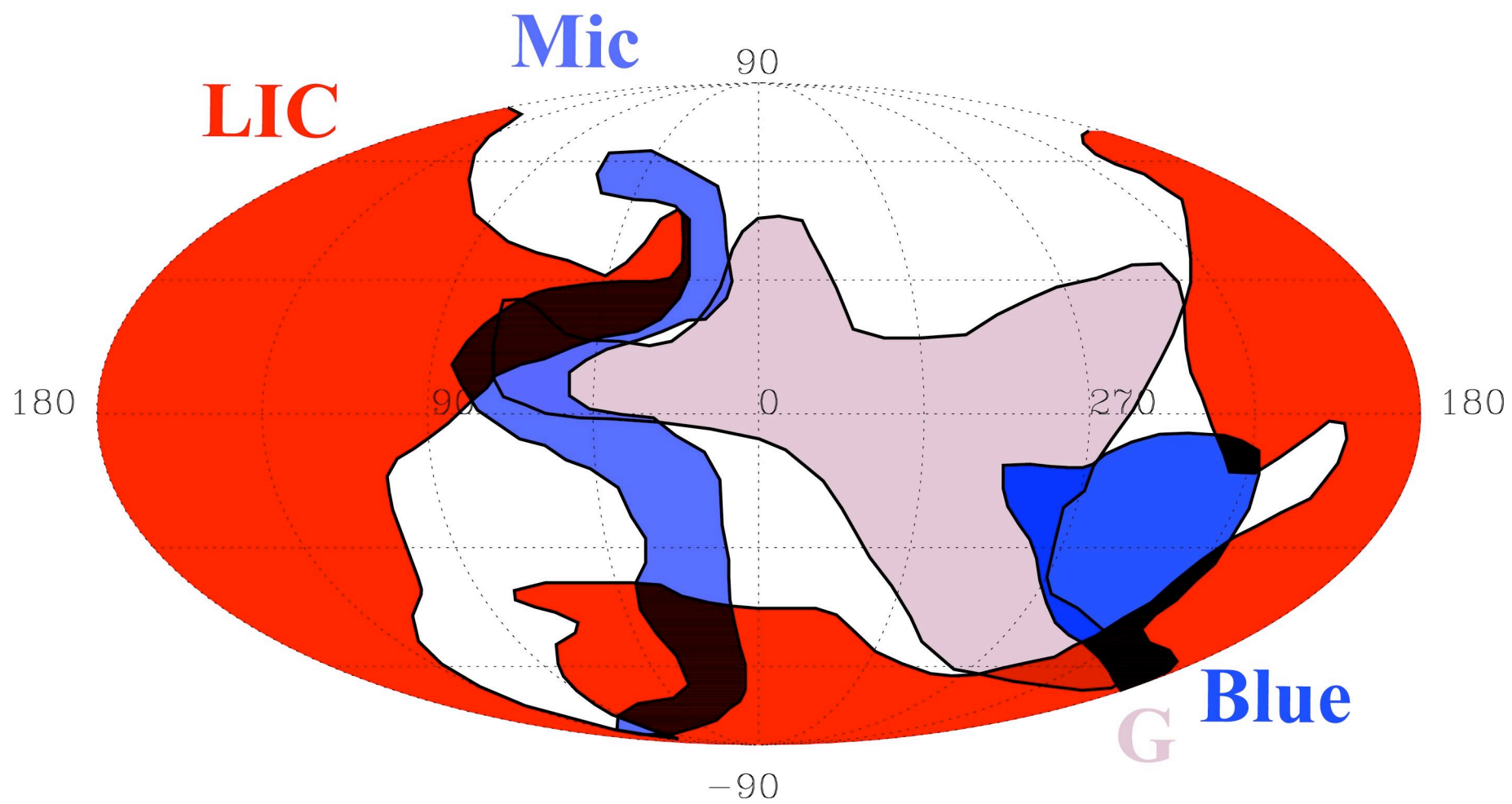
Given the temperature and density of the LISM, the thermal sound speed is $\sim 8 \text{ km/s}$.

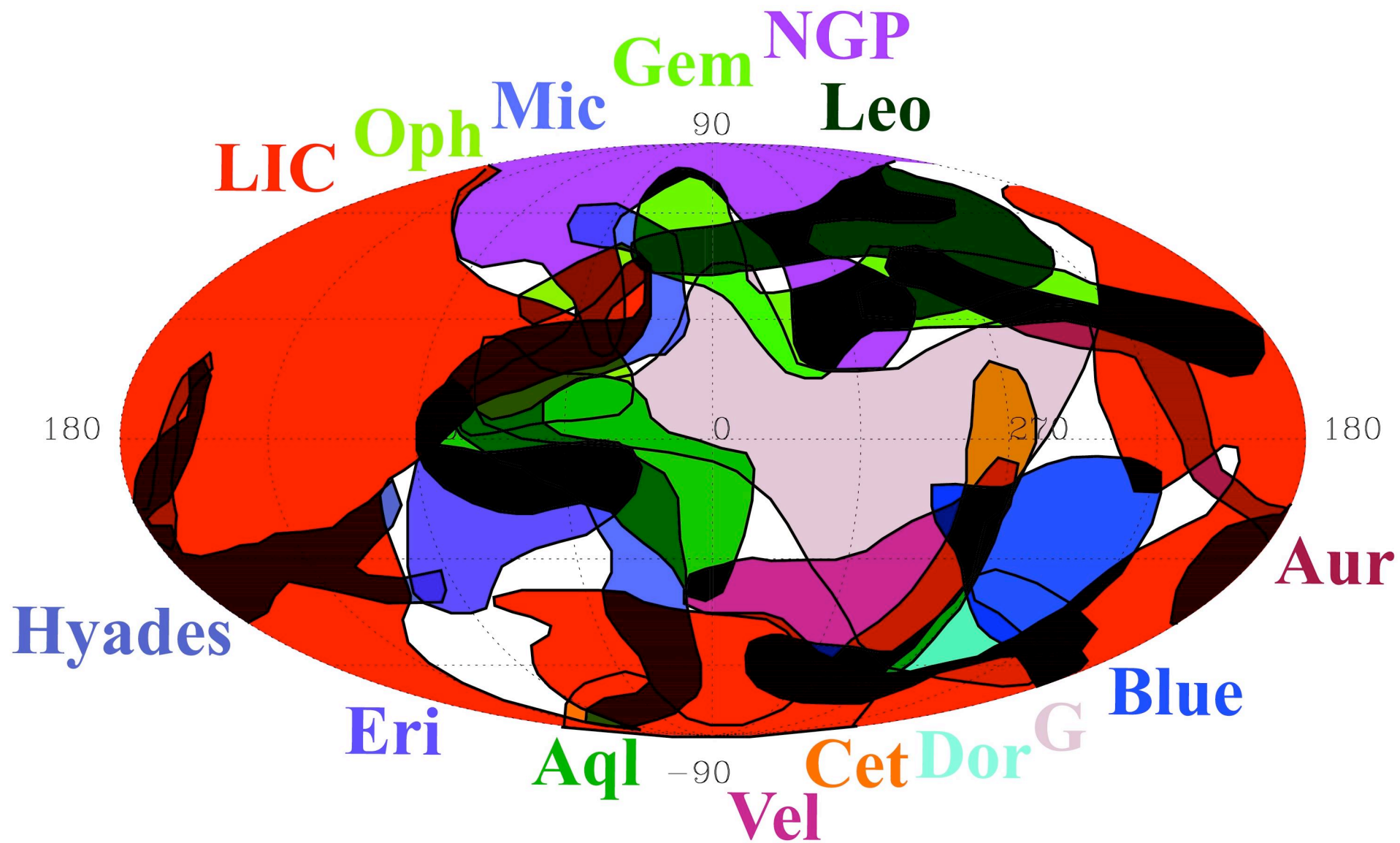
Measured turbulent velocity is a sightline-averaged quantity, and high velocity turbulent motions may exist.



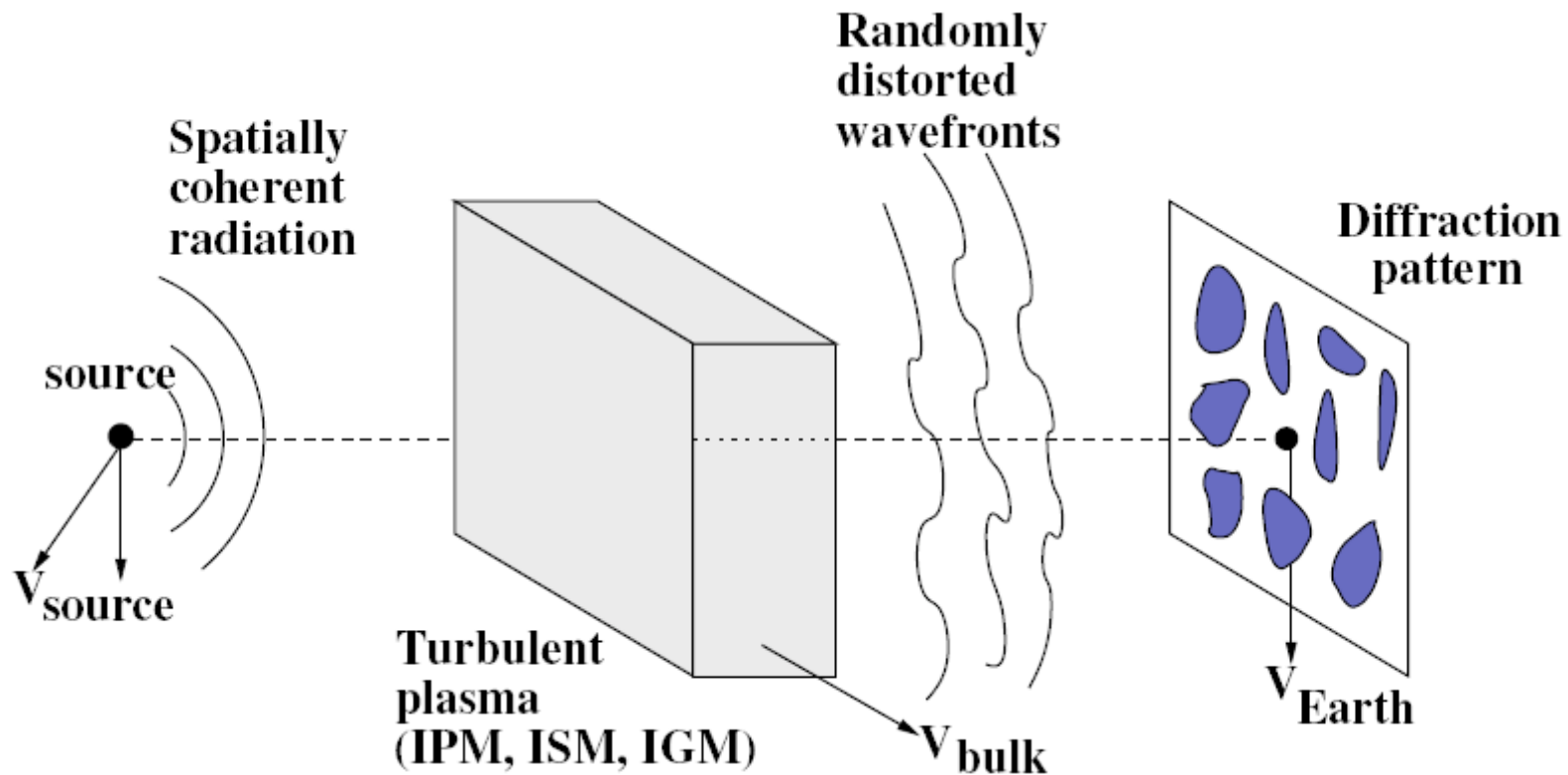
Is the Sun located inside the LIC or the G Cloud?
(Redfield & Linsky ApJ 673, 283 (2008))

Parameter	Interstellar He atoms inside the heliosphere	LIC	G Cloud
V (km/s) (upwind)	26.24±0.45 (Möbius et al. 2004)	23.84±0.90 (79 LOS)	29.6±1.1 (21 LOS)
T (K)	6300±390 (Möbius et al. 2004)	7500±1300 (19 LOS)	5500±400 (5 LOS)





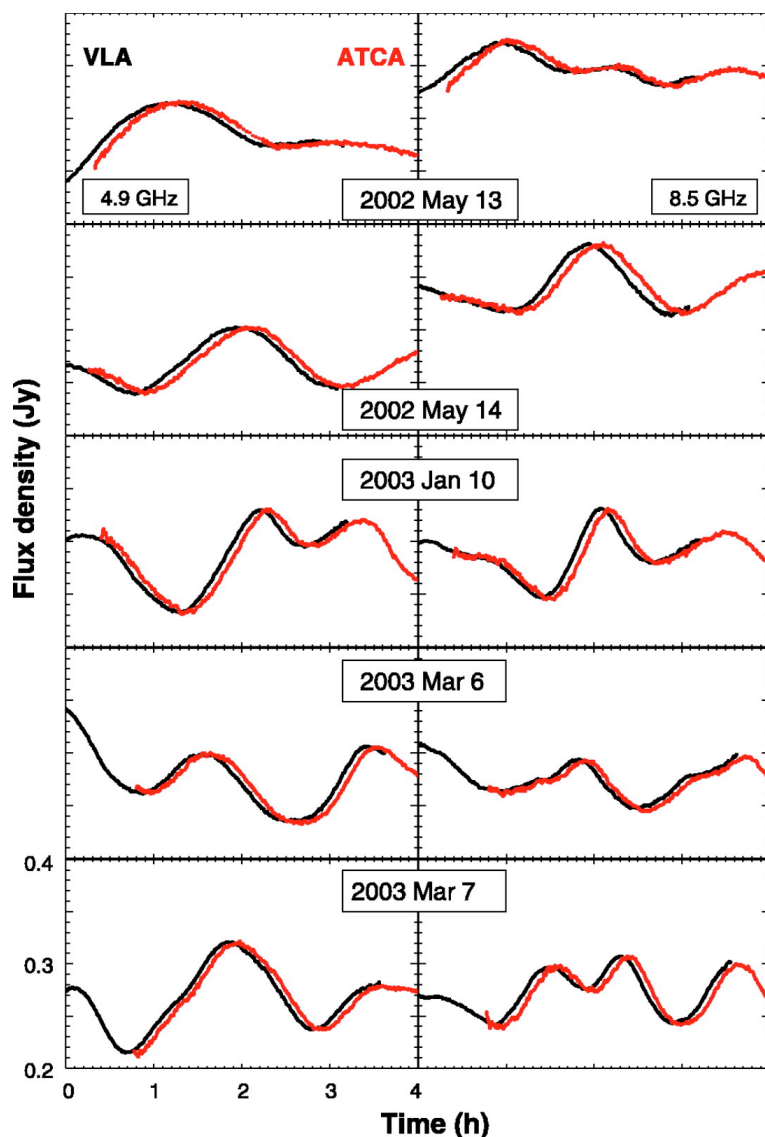
Geometry for radio-wave (and optical-wave) propagation in the ISM (Cordes et al. ASP 365, 233 (2007))



Comparison of optical and radio seeing. Effect of refractive index variations through a perturbing medium at the distance of the observer

Wave-length	Distance to perturber	r_0 (Fried)	t_0	What moves?
Optical (5000 Å)	m-km	10-20 cm	10 ms	Cells in Earth's atmosphere
Radio (6 cm)	pc	$\sim 10^5$ km	years	Earth relative to ISM

Radio Scintillation: IntraDay Variables (IDVs)



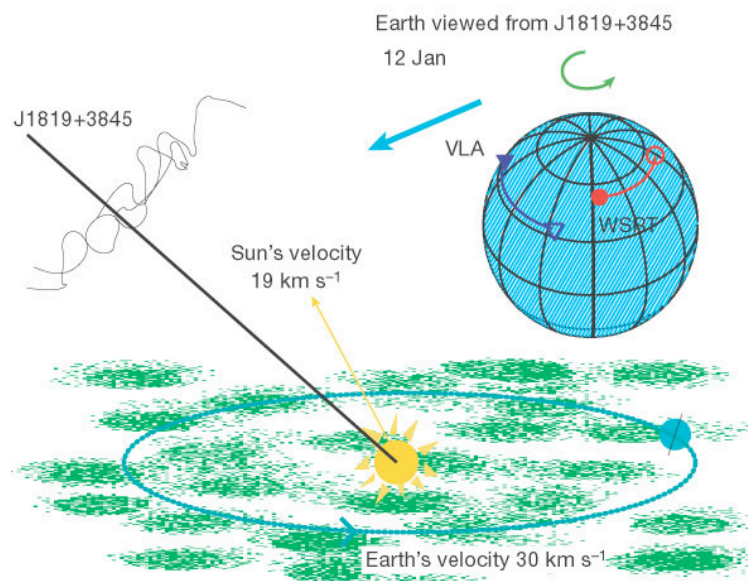
Bignall et al. (2006)

1% of all radio quasars show short timescale variability (hours).

Diffraction of intervening screen can cause time delays in signal - *use to get transverse motion of scintillating screen.*

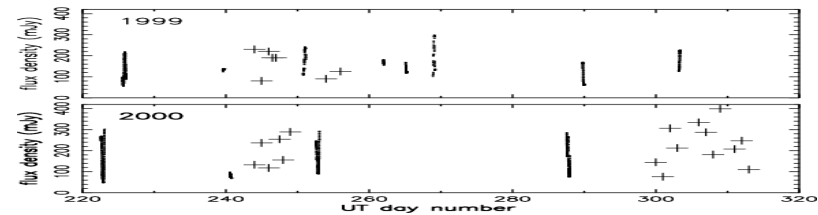
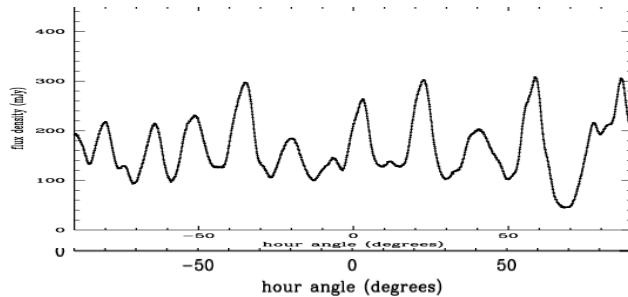
As Earth moves through projection of diffraction pattern, the characteristic timescale of scintillation varies - which is repeatable over several years.

Set characteristic scale length ($\sim 10^4$ km) to Fresnel scale to put limits on screen distance: $L < 10$ pc!



Dennett-Thorpe & de Bruyn (2002)

Interstellar scintillations (ISS) observed in the radio produced by turbulent scattering screens

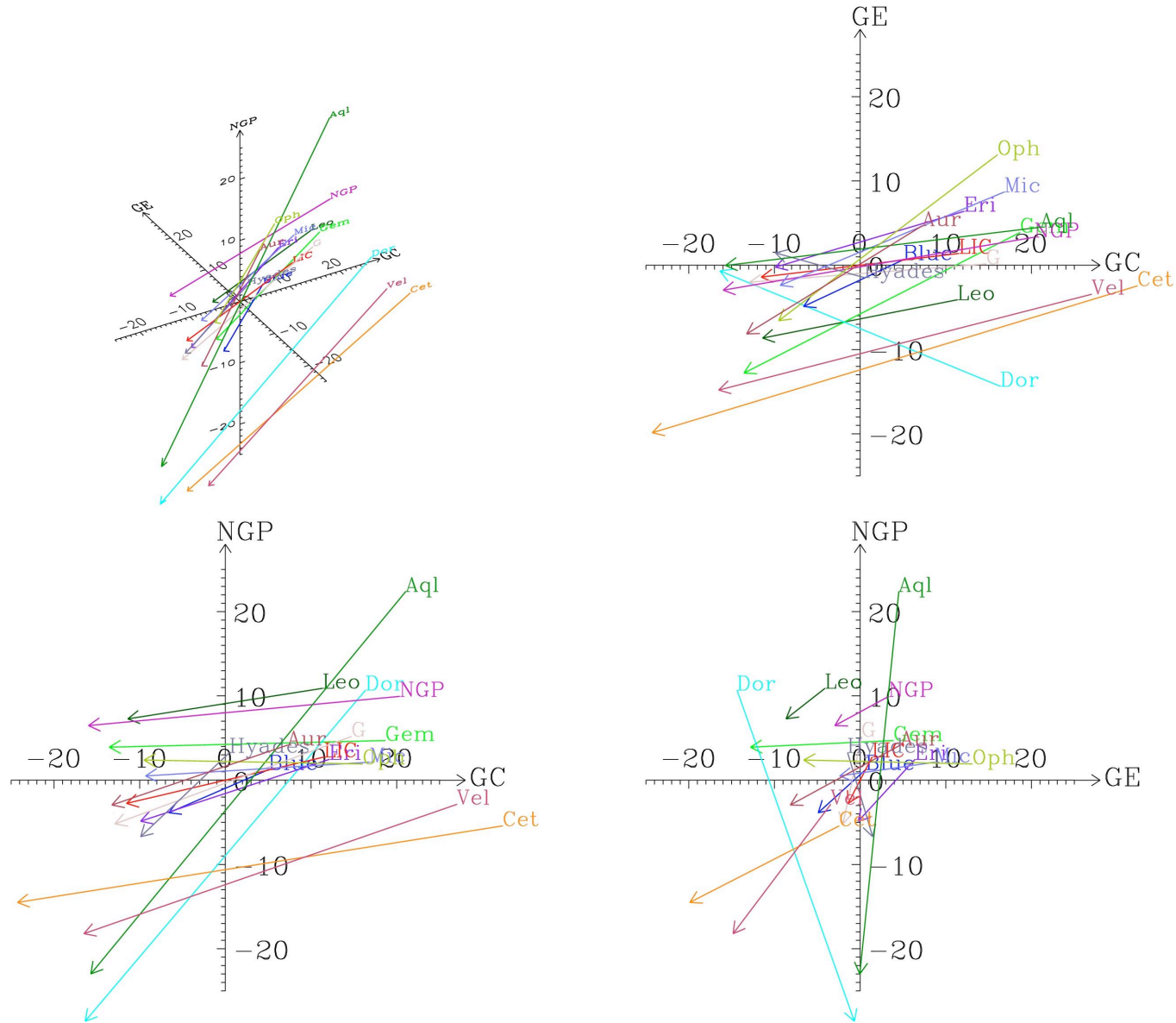


- Example of the quasar J1819+3845 (Dennett-Thorpe & de Bruyn (A +A 404, 113 (2003)).
- “Twinkling” of quasars and pulsars with small angular diameters by nearby turbulent plasma in the ISM.
- Amplitude and time scale of flux variations depends on changing speed at which the Earth cuts through the scintillation pattern projected onto the solar system as the Earth moves around the Sun.

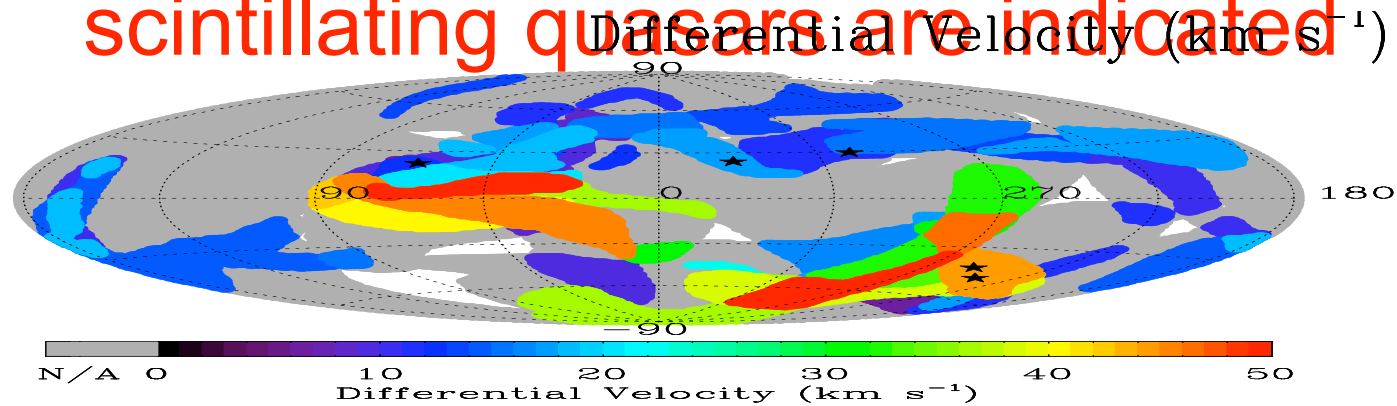
Well studied scintillation sources

Background Sources	Galactic Longitude	Galactic Latitude	Screen Distance (pc)	Warm Cloud Boundaries near sources
J1819+3845	66	+22	1.6 ± 1	LIC,G,Mic, Oph
PKS 1257-326	305	+30	<10	G,Gem,Leo, NGP,Aur
PKS 0405-385	241	-48	~10	LIC,G,Blue, Dor,Cet,Vel
PSR J0437-4715	253	-42	~10	same

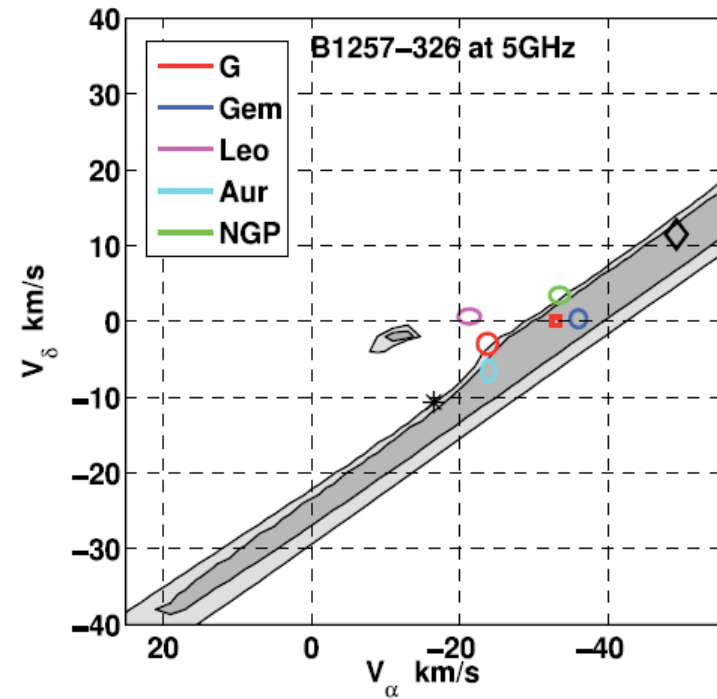
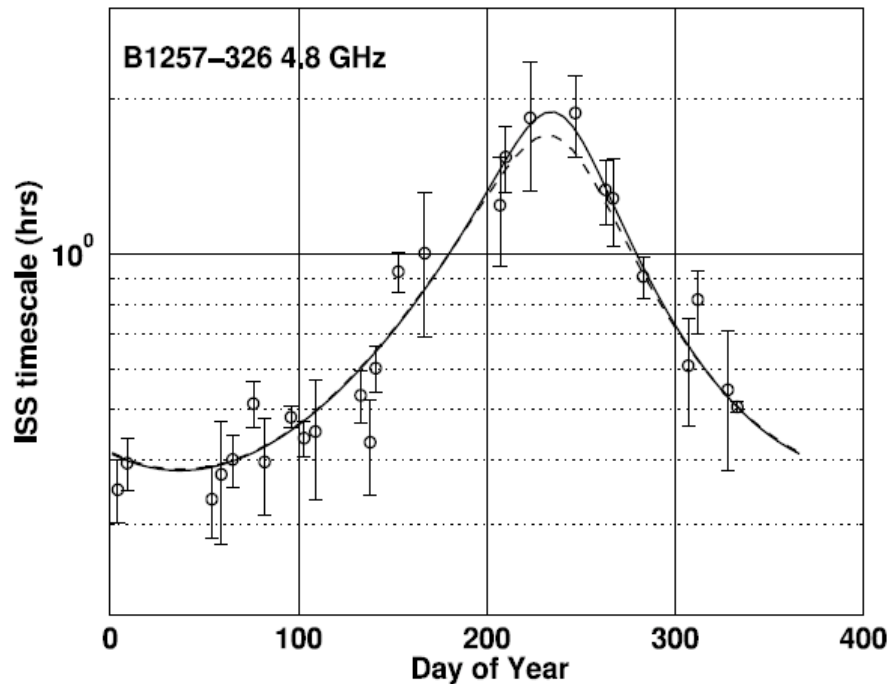
Heliocentric Vector Solutions



Differential velocity between LISM clouds
along same line of sight. Large amplitude
scintillating quasars are indicated

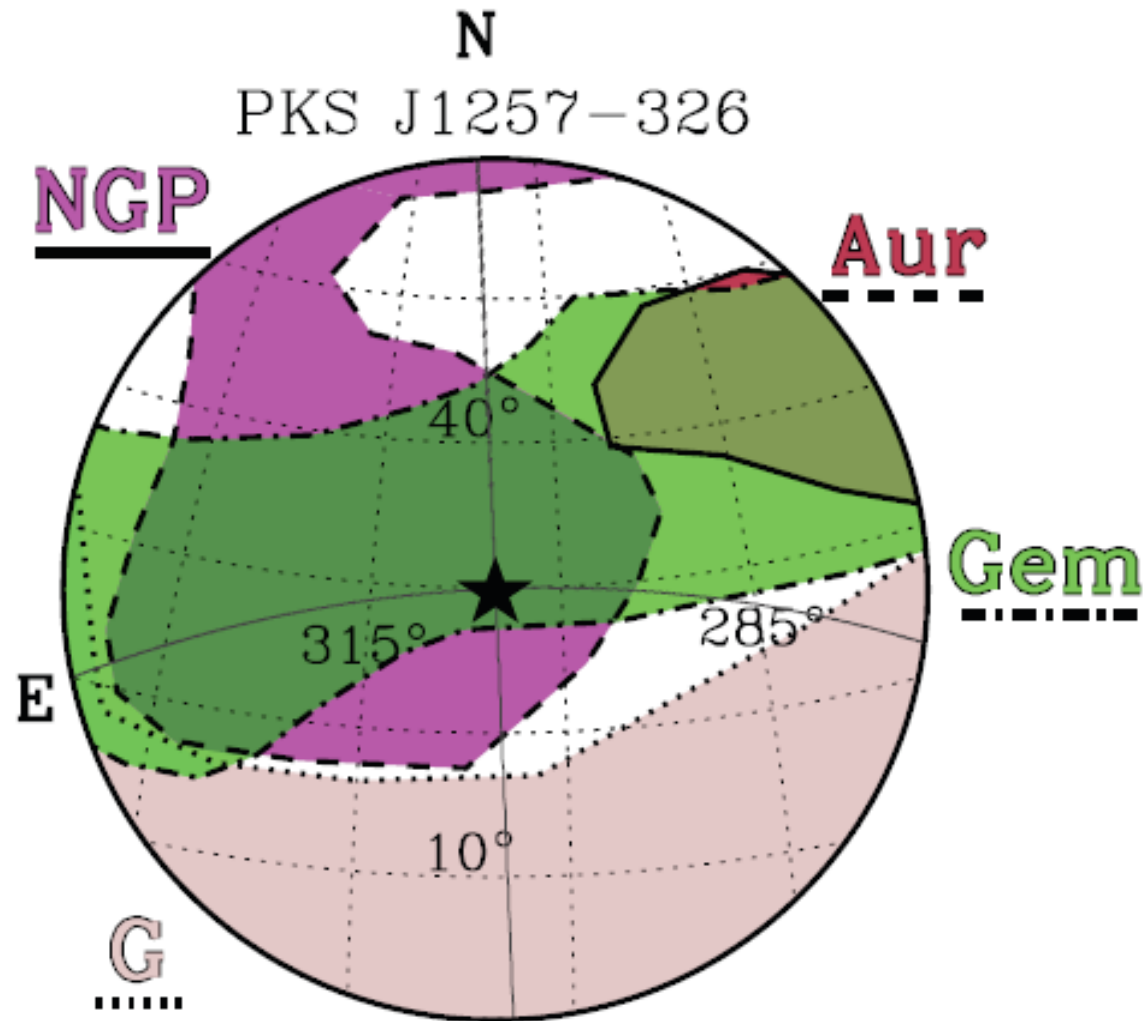


Left: Intrahour 4.8 GHz flux variability compared with best 5-parameter fit (solid) and fit with Gem cloud transverse velocity (dashed)

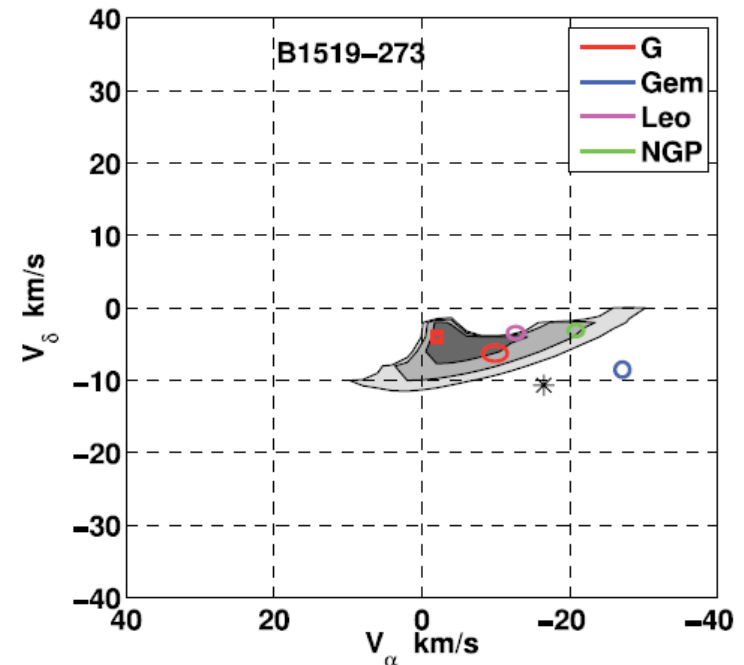
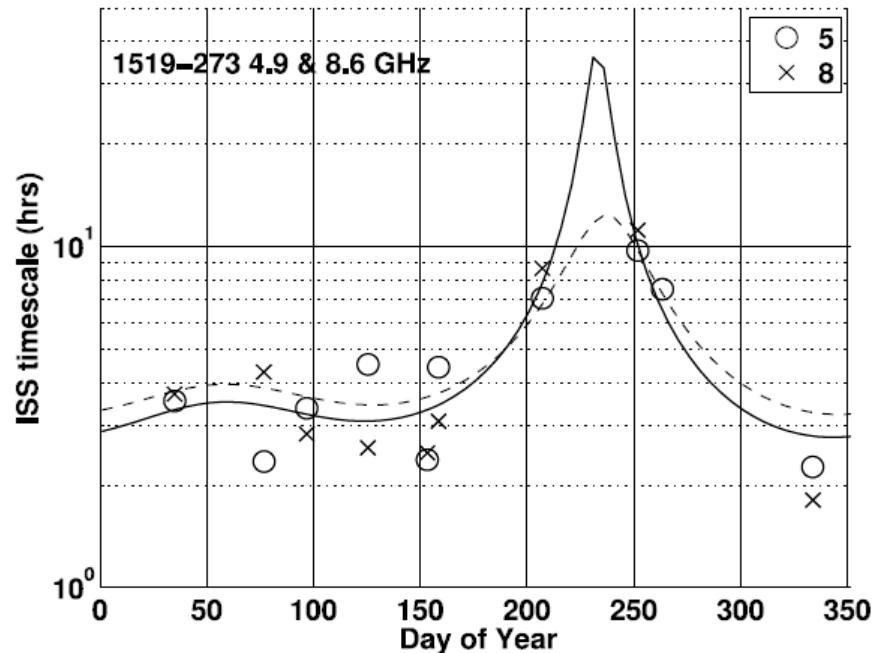


Right: Search in transverse velocity space for best 3-parameter fits to the ISS timescale data. Contours are for $X^2=1.2$ and 1.4 . ■ is best 5-parameter fit. * is best fit for transverse velocity of LSR. Gem and Aur are best cloud matches.

Clouds located within 30° of quasar J1257-326. Line of sight to the quasar passes through edge of Gem Cloud with NGP Cloud overlap. Aur Cloud is 15° away.

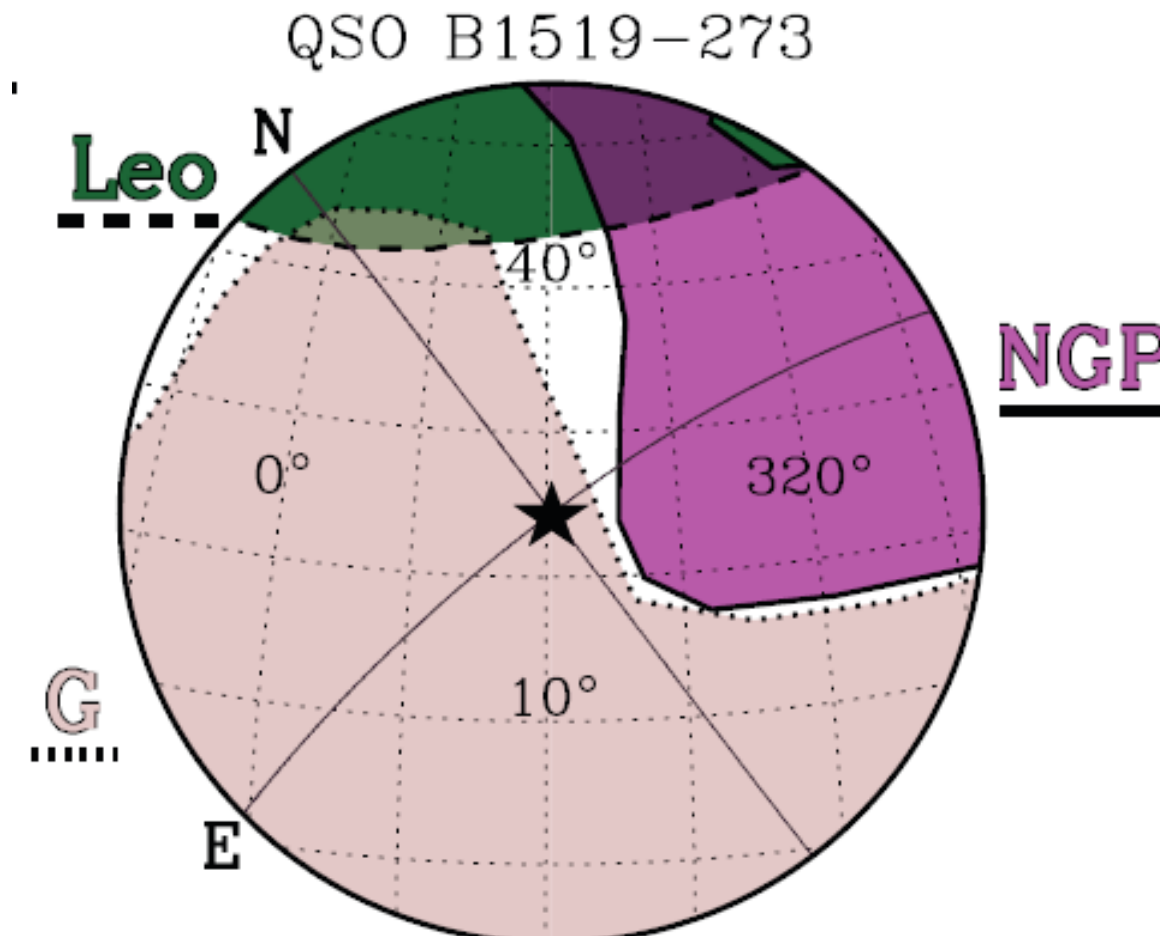


Left: Intrahour flux variability compared with best 5-parameter fit (solid) and fit with G Cloud transverse velocity (dashed)

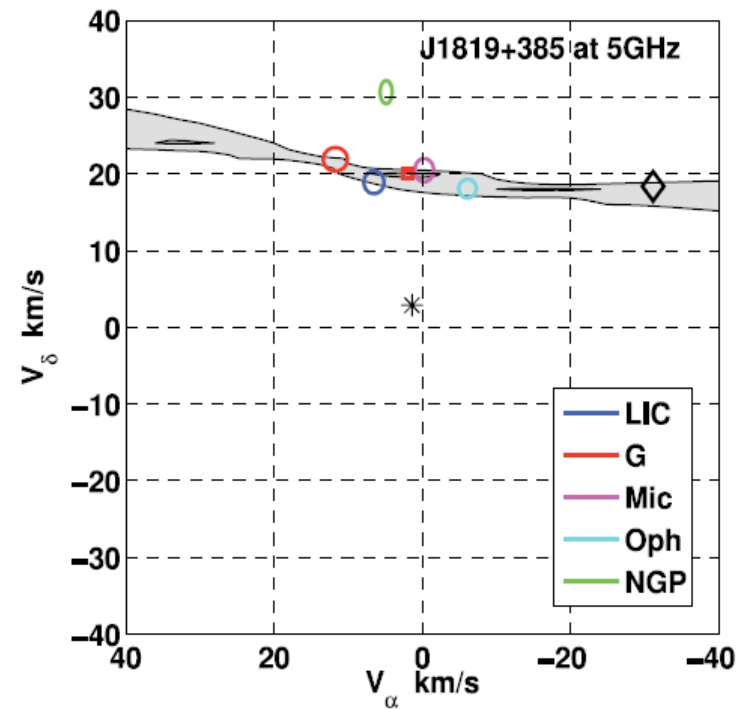
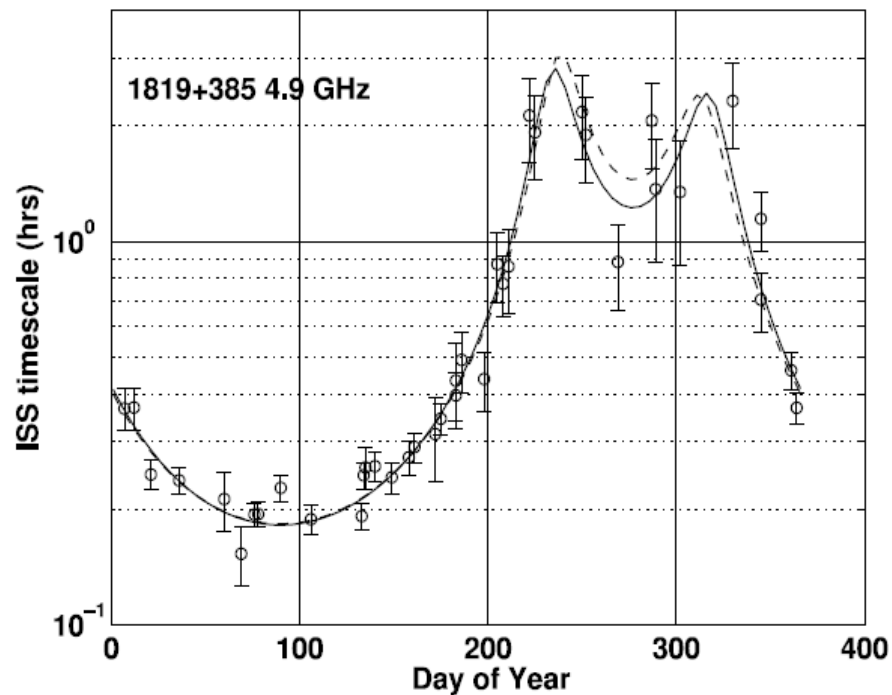


Right: Search in transverse velocity space for best 3-parameter fits to the ISS timescale data. Contours are for $\chi^2 = 1.2, 1.5, 2.0$. ■ is best 5-parameter fit. * is best fit for LSR transverse velocity. Best cloud matches are for G and Leo.

Clouds located within 30° of quasar 1519-273. Line of sight to the quasar passes through edge of G Cloud with NGP nearby. Leo Cloud is 20° away.

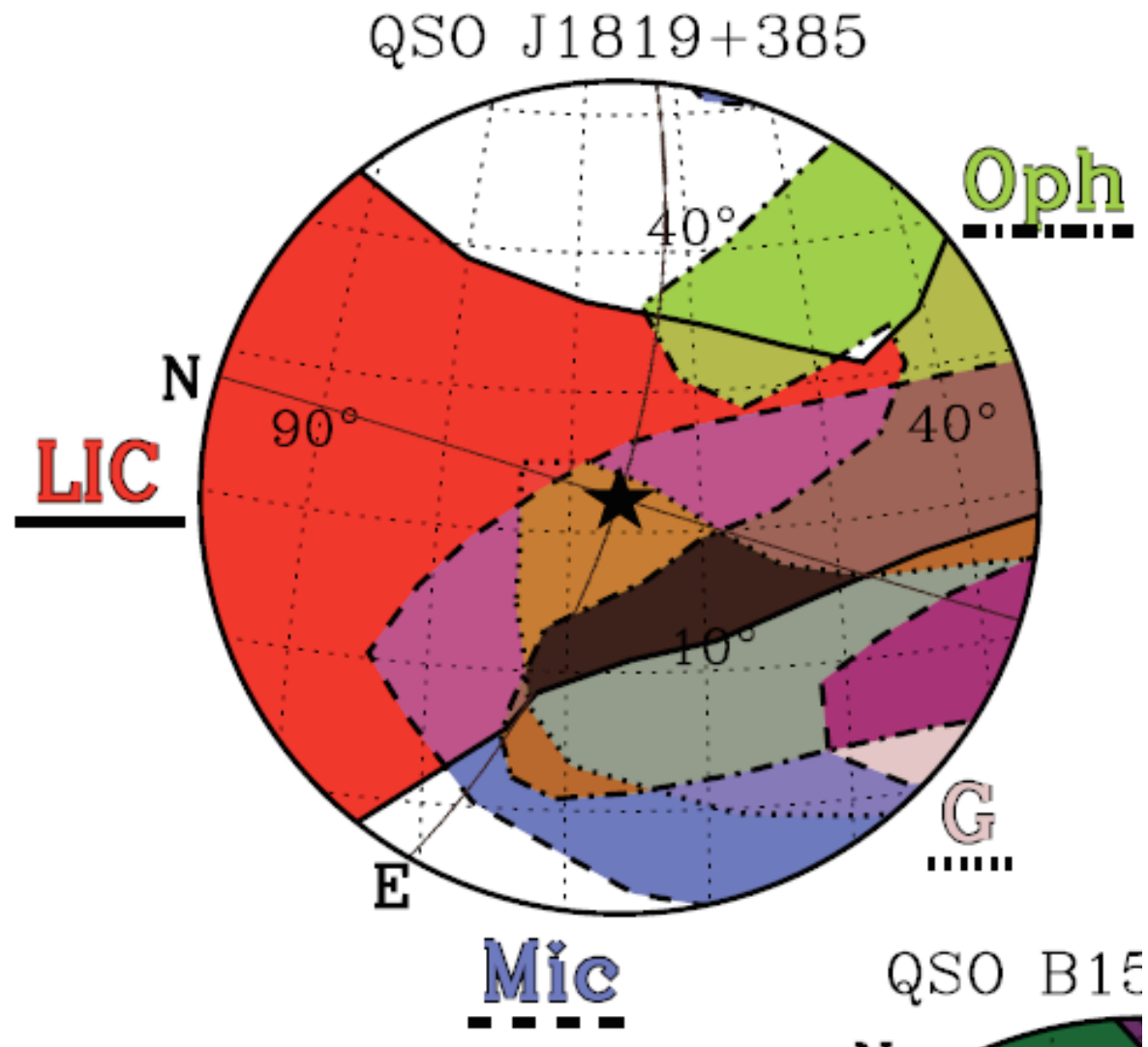


Left: Intrahour flux variability compared with best 5-parameter fit (solid) and fit with Mic Cloud transverse velocity (dashed)



Right: Search in transverse velocity space for best 3-parameter fits to the ISS timescale data. Contours are for $X^2=1.2, 1.5$. \blacksquare is best 5-parameter fit. * is transverse velocity of the LSR. Mic and LIC Clouds are best cloud matches. G and Oph Clouds acceptable matches.

Clouds located within 30° of quasar 1819+385.
Line of sight to the quasar passes through edges
of Mic LIC, and G Clouds.



Summary

Local ISM

- Identify 15 warm clouds located within 15 pc of the Sun.
- LOS V_{rad} consistent with a velocity vector ($\Delta V < 1$ km/s) for each cloud.
- Range of T , ξ , $D(\text{Fe})$, $D(\text{Mg})$ between clouds.
- Along many lines of sight the velocity differences between clouds are large.
- Interesting dynamics and cloud-cloud interactions.

Radio Scintillation

- Scintillation screens can be assigned to nearby warm clouds by transverse velocities.
- 1257 screen near edge of Gem cloud. Overlaps NGP.
- 1519 screen near edge of G cloud. Close to NGP.
- 1819 screen where Mic, LIC, and G clouds interact.
- Turbulence likely due to velocity differences at cloud edges where clouds interact.

More details can be found in the following papers

- Seth Redfield & Jeffrey L. Linsky, “The Structure of the Local ISM: Dynamics, Morphology, Physical Properties, and Implications of Cloud-Cloud Interactions”
ApJ 673, 283 (2008)
- Jeffrey L. Linsky, Barney J. Rickett, and Seth Redfield, “The Origin of Radio Scintillation in the Local ISM”, *ApJ* 675, 413 (2008)